

**NASA  
SPACE VEHICLE  
DESIGN CRITERIA  
(STRUCTURES)**

**NASA SP-8060**

# **COMPARTMENT VENTING**



PROPERTY OF  
MARSHALL LIBRARY  
A&TS MS-IL

**NOVEMBER 1970**

**NATIONAL AERONAUTICS AND SPACE ADMINISTRATION**

## GUIDE TO THE USE OF THIS MONOGRAPH

The purpose of this monograph is to provide a uniform basis for design of flightworthy structure. It summarizes for use in space vehicle development the significant experience and knowledge accumulated in research, development, and operational programs to date. It can be used to improve consistency in design, efficiency of the design effort, and confidence in the structure. All monographs in this series employ the same basic format – three major sections preceded by a brief INTRODUCTION, Section 1, and complemented by a set of REFERENCES.

The STATE OF THE ART, Section 2, reviews and assesses current design practices and identifies important aspects of the present state of technology. Selected references are cited to supply supporting information. This section serves as a survey of the subject that provides background material and prepares a proper technological base for the DESIGN CRITERIA and RECOMMENDED PRACTICES.

The DESIGN CRITERIA, Section 3, state *what* rules, guides, or limitations must be imposed to ensure flightworthiness. The criteria can serve as a checklist for guiding a design or assessing its adequacy.

The RECOMMENDED PRACTICES, Section 4, state *how* to satisfy the criteria. Whenever possible, the best procedure is described; when this cannot be done, appropriate references are suggested. These practices, in conjunction with the criteria, provide guidance to the formulation of requirements for vehicle design and evaluation.

## FOREWORD

NASA experience has indicated a need for uniform criteria for the design of space vehicles. Accordingly, criteria are being developed in the following areas of technology:

Environment  
Structures  
Guidance and Control  
Chemical Propulsion

Individual components of this work will be issued as separate monographs as soon as they are completed. A list of all published monographs in this series can be found at the end of this document.

These monographs are to be regarded as *guides* to the formulation of design requirements and specifications by NASA Centers and project offices.

This monograph was prepared under the cognizance of the Langley Research Center. The Task Manager was A. L. Braslow. The author was J. T. Francisco of Martin Marietta Corporation. A number of other individuals assisted in developing the material and reviewing the drafts. In particular, the significant contributions made by H. P. Adam, E. C. Cady, and H. R. Melton of McDonnell Douglas Corporation; A. Africano and H. Sexton of North American Rockwell Corporation; R. H. Miller of The Boeing Company; R. J. Muraca of NASA Langley Research Center; E. A. Rawls of Chrysler Corporation; R. T. Reid of Lockheed Missiles & Space Company; H. L. Simmons and G. Tarnower of LTV Aerospace Corporation; C. J. Studerus of General Electric Company; and P. S. Yip of General Dynamics Corporation are hereby acknowledged.

NASA plans to update this monograph when need is established. Comments and recommended changes in the technical content are invited and should be forwarded to the attention of the Design Criteria Office, Langley Research Center, Hampton, Virginia 23365.

November 1970

# CONTENTS

1.	INTRODUCTION . . . . .	1
2.	STATE OF THE ART . . . . .	3
2.1	External Flow Field . . . . .	4
2.2	Vent-Flow Processes . . . . .	5
2.3	Compartment-Flow Field . . . . .	7
2.4	Verification of Vent-System Performance . . . . .	10
3.	CRITERIA . . . . .	11
3.1	Analysis . . . . .	11
3.2	Design Constraints on Vent Selection . . . . .	12
3.3	Verification of Vent-System Performance . . . . .	12
4.	RECOMMENDED PRACTICES . . . . .	13
4.1	Analysis . . . . .	13
4.1.1	External Flow Field . . . . .	13
4.1.2	Vent Flow . . . . .	13
4.1.3	Compartment-Fluid Flow . . . . .	15
4.2	Design Constraints on Vent Selection . . . . .	17
4.3	Verification of Vent-System Performance . . . . .	19
	REFERENCES . . . . .	21
	NASA SPACE VEHICLE DESIGN CRITERIA MONOGRAPHS ISSUED TO DATE . . . . .	25

# COMPARTMENT VENTING

## 1. INTRODUCTION

Space vehicles contain many compartments whose walls may be subjected to critical loads imposed by pressure differentials across them. These compartments include not only such obvious enclosures as interstages, payload shrouds, and fairings, but also enclosures such as heat shields, insulation panels (e.g., multilayer blankets and foam), honeycomb and corrugated sandwich structure, and housings for electronic equipment and conduits. Pressure differentials cause bursting or crushing loads which may result in tension, compression, or shear failures; even relatively small differentials may be critical when imposed simultaneously with compressive axial loads in such a way as to induce beam-column buckling.

Bursting or crushing and buckling pressure loads have caused structural failure during space-vehicle flights. A complete launch vehicle failed because an external vent was in the region of a normal shock. Tests were conducted on a small-scale model with orifices spaced close together; however, on the full-scale vehicle, where the pressure data points were spaced farther apart by the scale factor, a vent was inadvertently placed on the wrong side of the normal shock, causing excessive pressure under a heat shield, followed by a destructive failure. At least one other flight failure has been attributed to the improper consideration of differential pressures across a payload-adaptor section.

Sudden failure of upper stage insulation panels has been attributed to improper venting. In one instance, base-heating shields required redesign to permit them to withstand the crushing pressures caused by the pressure pulse associated with engine ignitions. In this case, the collapse pressures were the sum of the engine overpressure plus a compartment underpressure due to adverse phasing of the external and internal pressures. In other cases, boxes for electronic equipment have exploded because decreases in external pressure were not considered in design. Honeycomb sandwich structures have also failed by delamination from bursting pressures caused by entrapped air in the honeycomb cells. Component failure also could possibly result from the deflection of thin-walled diaphragms into critical payload regions when the diaphragms are not properly restrained.

Venting problems do not always involve structural failure. For example, engine failures during flight have been attributed to insufficient venting of interstages during engine startup. Electric-wiring failures have been caused by heating from hot external air ingested through vents. Spacecraft performance has also been degraded by contaminants which entered payload-shroud vents.

The basic design problem in compartment venting is limiting the magnitude of differential pressures or minimizing the adverse effects of differential pressure through the use of favorable vent paths, vent areas, and external orifice configurations and locations. The design of a satisfactory vent system, however, is complicated by numerous constraints imposed by the structure, internal equipment, and subsystems which must be considered throughout the design and analysis of a vent system. Some of these constraints are:

- Compartment geometry and the volume and location of internal equipment are generally fixed and may influence the vent-flow process.
- Minimum bursting-pressure differentials may be imposed during ascent to provide a pressure-stiffening effect to avoid panel flutter.
- The rate of change of pressure in a compartment during ascent or entry, as well as absolute pressure levels, may affect internal structure and equipment.
- Payload-contamination limits may restrict the allowable mass flow into the compartment.
- Temperature limits may be imposed by heat-sensitive equipment.
- The inflight venting system must be compatible with the prelaunch venting requirements for ground air conditioning, insulation purging, and propellant-fume ventilation.

The complexity of all these interrelationships demands that a systematic approach be followed in the design of the venting system. Before a system can be selected, however, the sensitivity of the space vehicle and the equipment inside the compartment to the possible environmental variations that different venting systems may cause must be understood. Whenever the various demands are incompatible, an impact analysis is conducted to determine what design requirements can be most readily modified. Only upon selection of a venting system which meets all conceptual needs can a venting analysis be initiated.

This monograph presents guidance for the analysis, selection, and verification of means of providing adequate venting of gases between internal compartments and between internal compartments and the external atmosphere. The monograph treats the prediction of flow rates through planned and unplanned vents and the internal environments and pressure differentials across compartment walls. The flow-rate prediction is discussed in the following terms: (1) the definition of the external flow field; (2) the definition of the flow processes between the external field and the compartment; and (3) the definition of the compartment-flow field. Various types of vents are appraised, their design constraints indicated, and guides presented for the location and sizing of vents. Verification of vent-system performance through analysis and testing is also discussed.

Related subjects are discussed in other published and planned monographs in this series. Pressure vessels, such as propellant tanks, also require the venting of gases and are treated in separate monographs. The definition of the external flow field during launch and ascent and during entry is to be treated extensively in two forthcoming monographs. In this monograph, the discussion of the external flow field is limited to data needed for analyses and testing.

## **2. STATE OF THE ART**

Venting for structural reasons is sometimes not provided for compartments designed for loading conditions more severe than those imposed by maximum attainable pressure differential across the walls. When loads caused by pressure differentials do affect a design, a sophisticated analysis of the pressure differentials occurring with planned venting and/or leakage through joints, gaps, or ducts is sometimes necessary to permit decreases in material thickness and weight. Sophisticated venting analyses are also sometimes performed for reasons other than to determine structural loads; for example, they may be conducted to account for heating of internal components, voltage breakdown, loss of lubrication, or deterioration of materials.

The flow fields considered in the analyses are illustrated in figure 1. The external flow-field environment varies not only with time but also with position over the vehicle. For the case illustrated, it is possible for Flow 1 to enter Compartment 1 and for Flow 2 to leave Compartment 1 at the same time. The vent system includes not only the openings between the compartment and the external environment but also the openings between compartments and such unplanned leakage areas as the joint between the cone and cylinder and the seams in metallic heat shields shown in figure 1. In the figure the vents include simple orifices, allowing flow between the external field and Compartment 1 and the tunnel allowing flow between Compartments 1 and 2. Within the compartment the various flows are mixed and distributed in a complicated

manner because of outgassing material, planned and unplanned passageways, heat transfer, free volumes, types of gas, the number of interconnected compartments, and other factors.

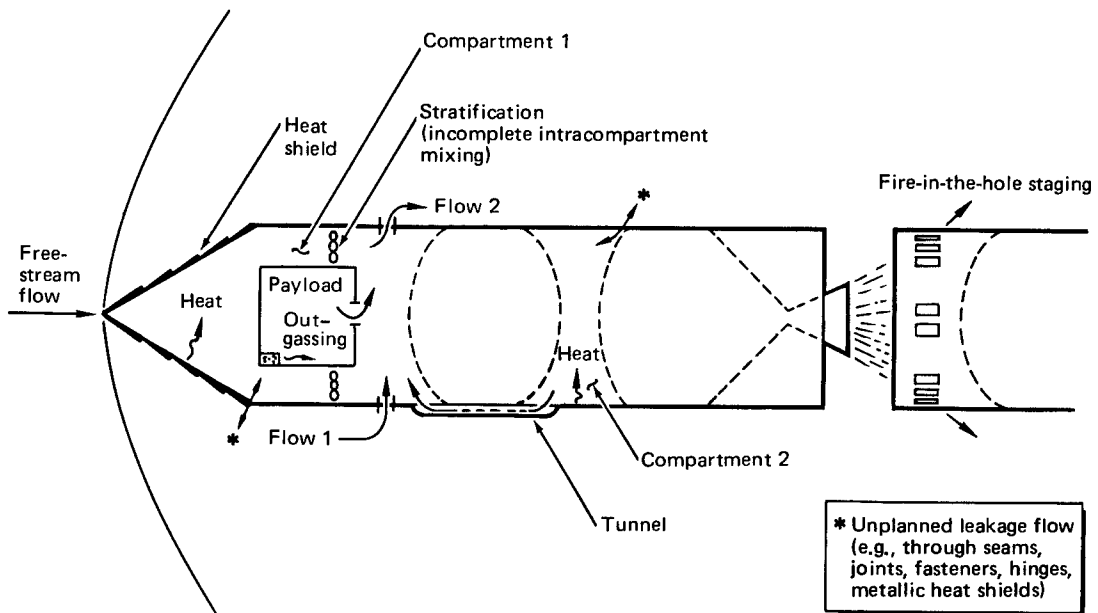


Figure 1. — Compartment-venting system.

The analytical procedures used for each flow field are not necessarily the same. Indeed, experimental data may be required to analyze one region, while another may be handled adequately with theory.

## 2.1 External Flow Field

The external flow field that exists during atmospheric flight produces a pressure distribution over the structure and determines the rates of energy and mass transfer through the vents. (Determination of the external flow field is discussed in some detail in reference 1 and in other monographs now in preparation.) More detailed analysis is required of the pressure distribution at vent locations than elsewhere on the vehicle. The flow rates through vents are very sensitive to variations of pressure at the vent, making definition of the location of standing shock waves extremely important. Because of variations in Mach number during flight, the shock waves, even when steady, appear to move, and their detailed position may depend upon the vehicle-attitude history. These detailed positions are difficult to determine from the type of data normally available from wind-tunnel pressure tests.



## 2.2 Vent-Flow Processes

The presence of flow through the vents can modify the external pressure distribution. Figure 2 (from ref. 2) illustrates the complexity of the flow field around a vent because of supersonic external flow and flow leaving the vent. The exiting jet interacts with the external flow to form separated flow regions forward and aft of the vent. These separated flow regions cause a pressure change in the external field and produce an aerodynamic force and increased aerodynamic heating. Moreover, if the jet is subsonic, the disturbance it induces in the surrounding flow field will in turn affect the strength of the jet. If the flow through the vent enters the compartment, the disturbance of the flow field is less pronounced but can have an effect on the mass-flow rate through the vent, which must be accounted for in analysis.

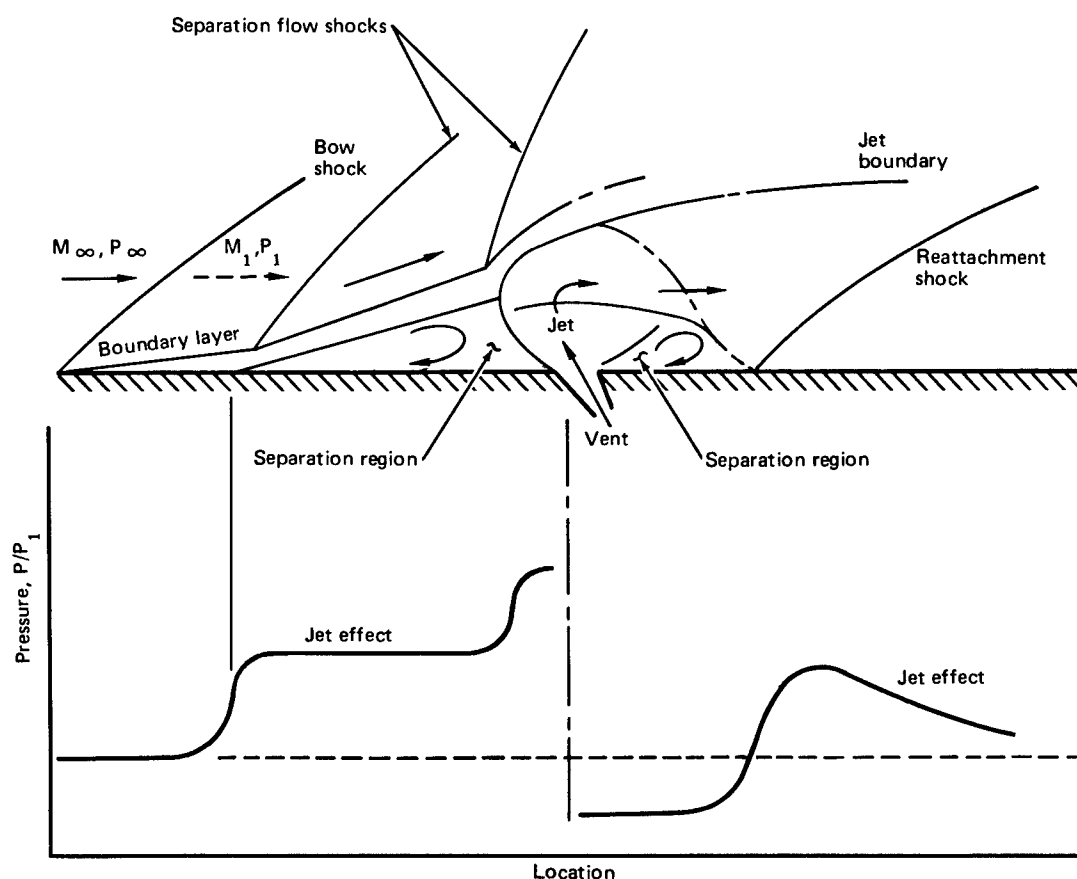


Figure 2. — Jet interaction with external flow.

The prediction of the interaction of the freestream flow field and the vent is extremely complicated and is largely an empirical exercise (refs. 2 and 3), even under ideal circumstances where the flow conditions approaching the vent outside the boundary layer and the detailed nature of the boundary layer are known. Moreover, the energy

level of the gas of any flow entering the vent must be known in predicting freestream-vent interaction. Gas-energy level is discussed in reference 1 and will be treated in planned monographs on entry gasdynamic heating and on aerodynamic loading during launch and entry.

The locations and configuration of the vents are as important to compartment venting as the physical characteristics (e.g., volume, wall area, and shape) of the compartment itself. The location of the vents in a compartment affects the external flow field and discharge pressure (as described previously). Similarly, the condition of the compartment fluid will depend upon the vents. For example, some region of the compartment could be cooler or warmer than other regions, as discussed in Section 2.4.

Vents can be classified according to their geometry and corresponding flow behavior into the general categories of orifices, valves, tubes (or pipes or ducts), and porous materials.

Orifices, as treated in this monograph, include not only sharp- or square-edged openings, but nozzles and cracks or seams through which gases will pass in an unobstructed fashion. (Joints, gaps, and ducts which partially obstruct the flow are more appropriately treated as tubes or porous materials.) Orifice-flow rates are generally calculated by use of isentropic-flow formulas modified by empirically determined coefficients (nozzle efficiency and coefficient of discharge, as defined in ref. 4). Coefficients for orifice flow with no external flow are given in references 5 to 8; reference 9 provides a compilation of orifice coefficients from numerous sources and shows their dependence on Reynolds number and pressure ratio. The effect of the external flow on the orifice flow can also be predicted by isentropic-flow formulas modified by similar empirically determined coefficients (refs. 10 to 15).

Vent valves, including such flow-limiting devices as spring-loaded doors and flapper valves, are used whenever it is desirable to maintain a given pressure in the compartment or when flow must be restricted to one direction, regardless of the pressure differential. Valves have complicated flow paths, and their flow characteristics generally must be determined by experiment. Valve opening and closing behavior is usually nonlinear, and some hysteresis is to be expected. Moreover, valves are often sensitive to changes in temperature and acceleration. Accordingly, flow through a valve cannot be considered as either strictly isentropic or strictly adiabatic. It is generally assumed, however, that a valve is isentropic and, when open, is treated like an orifice with experimentally determined coefficients. The flow characteristics of valves are discussed in references 16 and 17.

A tube, pipe, or duct may be provided to channel the flow of a vented gas (e.g., the channeling of a flammable gas to an overboard dump). Ducts may also be used as electrical conduits, and gases may flow through them. Where the length-to-diameter ratio of the duct is large, friction losses and/or heat transfer may be significant. Perfect-gas solutions for both adiabatic flows with friction and nonadiabatic flows with no friction are tabulated in reference 18; the appropriateness of these solutions is discussed in references 4 and 17. Consideration of isothermal flow with heat transfer appears to provide an attractive solution to the problem of duct flow. However, the equations used in this approach require that heat transfer be considered infinite when the flow is choked (ref. 4). Similarly, difficulties arise with equations which can be written for flows with simultaneous heat transfer and friction (refs. 4 and 19) since solutions to these equations cannot be written in closed form.

Porosity of structural materials is a significant consideration in compartment-vent design only when pressure must be maintained for long periods of time, as in a spacecraft in orbit. Filters may be included in vents to prevent the passage of contaminants. The flows through porous media and filters may be continuous, slip, or free-molecule flows with more than one phase existing at once. Although much literature (e.g., refs. 17 and 20) exists on flow through porous media, it is usually related to oil and gas recovery and may not be applicable because of the extremely different Reynolds number, Knudsen number, and Mach number of the flows that occur in space-vehicle flights. Screens may also be added to vent openings for electromagnetic-field control. Data on the effect of screens on vent-orifice coefficients are presented in reference 21.

Any type of vent may be modified to meet special design requirements. For example, frangible diaphragms and mechanically or explosively ejected panels are used when the orifice must be sealed before being opened. Since an opening can be incomplete or have uneven orifice edges, the discharge coefficient of such an orifice can be a major unknown. Orifices opening rapidly can cause transient shocks which propagate through the gases into the compartment. This effect will be discussed in the following section.

## **2.3 Compartment-Flow Field**

There are three general sources of flow in a compartment:

1. Gas may enter the compartment through the vents from the external environment. Even if the external ambient pressure is steadily decreasing, local external pressure gradients on the spacecraft may cause the gas to enter vents. This flow can be more than a direct crossing through the compartment to exit at a second vent (fig. 1).

2. Flow may occur between connected compartments. Figure 1 illustrates such a flow passing through an external conduit.
3. Flow may originate within the compartment itself under certain circumstances. These circumstances include, but are not limited to, the following:
  - A. Venting from equipment packages
  - B. Exhausting of engine gases
  - C. Purging gases.
  - D. Leaking of liquids (which vaporize) and leaking or controlled venting of gas from pressurized containers
  - E. Outgassing of solid materials

The condition of flow in a compartment can be affected by sources other than fluids entering the compartment. Very hot structure, such as an external wall heated by induced external flow fields (ref. 1), and very cold structure, such as a tank wall at cryogenic temperatures, can cause significant changes in temperature of the compartment gases and subsequent changes in compartment flow.

In a typical compartment, the flow field may be extremely complicated because of relatively large dimensions and irregular geometry. However, it is often unnecessary to define the details of the internal flow because when variations in gas properties in the compartment are small (e.g., low velocities and small pressure and temperature gradients), the compartment gas can be assumed to be homogeneous, and the gasdynamic equations used in the analysis of the compartment flow can be greatly simplified. (Chs. 7, 15, and 22 of ref. 22, for example, present derivations of the generalized equations for the so-called macroscopic balances.)

Homogeneity implies that complete mixing (with essentially zero velocity) occurs within the compartment and, consequently, that the compartment pressure, temperature, and density are uniform at any time. Reference 9 presents the derivation of equations for flow of a homogeneous fluid under the additional restrictions of adiabatic and isentropic processes for a perfect gas. Variations in temperature resulting from heat transfer and incomplete mixing may be approximated in a variety of ways, depending on the magnitude of the temperature differences, the geometry of the compartment, and the mass flow in the compartment. Reference 23 gives an analytical procedure appropriate for use when conduction or free convection is the method of heat transfer. The introduction of gas of a different species or at a different

temperature than the gas in the compartment presents a mixing problem. References 17 and 24 discuss mixing by diffusion; reference 25 covers turbulent mixing; a method of handling combustion is given in reference 26. (When the gas is not essentially homogeneous, analysis becomes complicated and no single procedure can be used.)

If the mass flow into the compartment has high momentum, as when a rocket engine is fired into the compartment (so-called fire-in-the-hole staging), the assumption of uniform conditions will be invalid. In this situation, analysis is qualitative. Experimental approaches are required for quantitative solutions and will be discussed in Section 2.4.

The validity of analysis of the compartment-flow field is questionable because of the apparently restrictive assumption of homogeneity. However, reference 9 presents a comparison of analytical and experimental data. The experimental case described in this reference is for a set of three compartments, the first two venting through one orifice to the next compartment, the third venting through an orifice to a time-varying pressure field. A comparison with analytical data from reference 9, reproduced in figure 3, indicates that analytical and experimental data can be in good agreement.

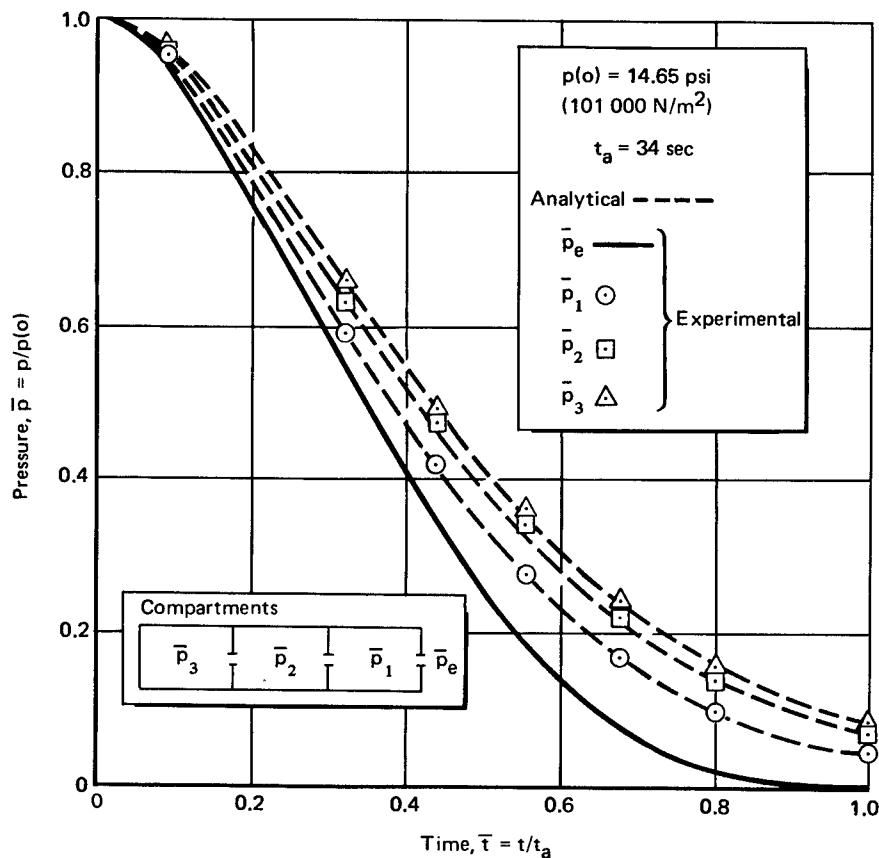


Figure 3. — Comparison of experimental and theoretical data for a three-volume model.

Generally, the analytical formulation for the case of homogeneous fluid in the compartment is possible only if the boundary conditions vary slowly. Whenever extremely rapid transients occur (e.g., moving shock waves near vents, blast waves which cause discontinuities in external conditions, explosively opened vents, or volume changes), homogeneous-compartment conditions cannot exist. Analysis of any of these conditions involves a characteristic solution which traces the propagation of waves through the compartment. References 4 and 27 to 29 provide an insight into the analytical procedure, but a general analytical approach does not exist. Tests now provide the only reliable way of obtaining good quantitative data.

## **2.4 Verification of Vent-System Performance**

Compartment-flow tests are required most frequently when homogeneous conditions do not exist in the compartment or when the compartment is subjected to rapid transients of the environment. Combined total system tests are desirable but are extremely difficult to perform because of the complexities of the interrelationships of the various aspects of compartment venting. Verification of system performance is therefore generally accomplished by a combination of analysis and tests conducted on subsystems, with the results combined analytically to obtain predictions of overall performance.

Facilities available for testing are described in references 30 to 32; test procedures used to measure discharge coefficients are discussed in references 10 to 15. Valid determination of these coefficients does not require simulation of the entire system but can be accomplished by simulation of the orifice geometry, the flow external to the orifice, and pressure differentials across the orifice (refs. 10 to 15). Auxiliary air is used to simulate the venting process; for example, see references 10, 12, and 15.

External Mach number and pressure with time are not simultaneously varied in current practice; however, by making use of vacuum chambers, variation in pressure rate can be simulated within certain size limitations. Heating and cooling of walls can be simulated with relative ease by using radiant heat lamps and cold fluids. Secondary air flow or even operating rocket engines can be used to simulate internal sources.

When there are secondary gas sources in the compartment, testing is performed also to verify analytical determination of compartment flow. Because such testing can become highly intricate and hence expensive, subscale tests are often conducted. However, the effect of scale size must always be accounted for. If the secondary gases are combustible when mixed with the ambient compartment gases, a subscale test may not be acceptable since the walls of a reduced-scale compartment have a greater quenching effect than the walls of a full-scale specimen.

Generally, when simulating a rocket engine as the secondary flow source, other parameters besides momentum flux and mass-flow rate must be represented in some detail. For example, a test may be needed to determine pressure distributions on a compartment's side walls. The details of these pressure distributions may be defined by the details of actual nozzle flow, including the Mach number and pressure distribution across the nozzle-exit plane and the boundary-layer effects of the nozzle wall. The starting sequence of the rocket engine must also be considered in the test plan [e.g., the dependence of the sequence on the starting technique (fuel or oxidizer lead if liquid-fueled engines, turbine-start cartridge, or solid-fueled rocket-motor igniter) and the rate of chamber-pressure rise]. In subscale tests, the applicability of the data also depends on variation of scale parameters.

### **3. CRITERIA**

All compartments of a space vehicle shall be analyzed to determine that the pressure differentials across all compartment walls and that the compartment environment are restricted within allowable limits. Adequate venting of space-vehicle compartments shall be provided to restrict these pressure differentials; otherwise, the walls of the compartment for which no venting is provided shall be designed to withstand the maximum attainable pressure differentials. The adequacy of vents for meeting all space-vehicle system requirements shall be verified by analysis or test, or combinations of both.

#### **3.1 Analysis**

All compartments shall be analyzed for proper venting. As a minimum, the following shall be accounted for:

- The external flow field and its pressure, temperature, and velocity over the space-vehicle surface
- Expected flight profiles, and associated dispersions with their resulting variations in Mach number, dynamic pressure, angle of attack, and angle of sideslip
- Characteristics and quantity of all internally produced gases (e.g., from venting of instrument compartments, reaction gases, outgassing of solid materials, from leaks and controlled venting of pressurized containers, and from propellant draining)
- The flow characteristics of the compartment vents, including interactions between the external flow field and the vented fluid

- Ingestion of external atmosphere, including leakages through unplanned vents, such as joints, gaps, and seams, which may be aggravated by the influence of static or dynamic loads or heating
- Heat transfer into and within the fluid in the compartment

The times that both the maximum and minimum compartment pressures occur shall be predicted to determine the times maximum bursting or crushing and pressure-buckling loads will occur. Sensitivity of analytical results to variations in the parameters shall be established. As a minimum, variations in trajectories (planned missions plus dispersions), tolerances in structural configurations, and uncertainties in experimental data shall be accounted for. The environment which affects the equipment and structure in the compartment shall be determined.

### **3.2 Design Constraints on Vent Selection**

Vents shall neither induce undesirable aerodynamic effects on the vehicle nor restrict the trajectories under which the vehicle may be operated.

In the selection of compartment vents, at least the following requirements and constraints shall be accounted for:

- Strength and structural characteristics of the compartment walls
- Strength and structural characteristics of equipment in the compartment
- Effects of vent fluid ingested into the compartment on equipment in the compartment
- Environmental tolerances of equipment in the compartment (both before and during flight)
- Compatibility with prelaunch gas-flow systems (e.g., ground air conditioning, insulation purging, and propellant-fume ventilation)

The design of any auxiliary mechanical venting equipment (e.g., valves, spring-loaded doors, or actuators) shall account for such special requirements as refurbishment or reuse, ease of manufacture, or sterilization.

### **3.3 Verification of Vent-System Performance**

Each theoretical assumption made in an analysis shall be identified and established to be valid or conservative. When this cannot be done, analytical procedures shall be



verified experimentally. When an analysis is not amenable to either theoretical or experimental verification, the analytical parameters (such as vent size, compartment volume, and trajectory data) shall be modified and the analysis repeated to establish a tolerance band. There shall be a high probability that the actual pressure differentials and environmental variables incurred in flight will fall within this band.

## **4. RECOMMENDED PRACTICES**

### **4.1 Analysis**

The following practices are recommended for venting analyses.

#### **4.1.1 External Flow Fluid**

The external pressure and temperature history in the vicinity of the compartment should be calculated on the basis of the vehicle's trajectory in the atmosphere and configuration, utilizing analytical techniques such as those described in reference 1. Other acceptable techniques are to be given in planned monographs on entry gasdynamic heating and aerodynamic loading during launch and entry. The model atmosphere (which determines the critical flow-field parameters) must be chosen judiciously. Many model atmospheres have been developed (e.g., model atmospheres of the earth in refs. 33 and 34 and the models of Mars and Venus in refs. 35 and 36, respectively). A perturbation analysis should be conducted to define vehicle dispersions. A minimum set of parameters to be examined, their effects, and an example of the magnitudes of the resulting dispersions are listed in table I. When the space vehicle has significant asymmetries, the directionality (plus or minus) of the perturbations can become important and should be taken into account.

#### **4.1.2 Vent Flow**

There is no way to size vents without performing an analysis. In these analyses, initial estimates of the vent area and of other critical vent parameters should be made with the use of a similarity parameter  $\left\{ \frac{CA}{V} \right\}^{1/2}$  ta

where

C = the average coefficient of orifice(s)

A = the total area of the vent(s)

V = the compartment volume

$t$  = a characteristic time during which pressure or other boundary conditions change

$a$  = the speed of sound of the gas in the compartment

TABLE I. — SOME PERTURBATIONS AND THEIR EFFECTS<sup>a</sup>

Perturbation parameter	Affected variable	Dispersion magnitude
External pressure at vent		
Wind velocity	Rigid-body angle of pitch	$\pm 6$ deg (0.105 rad)
Wind shear	Rigid-body angle of yaw	$\pm 6$ deg (0.105 rad)
Wind azimuth	Dynamic pressure	$\pm 200$ psf (9560 N/m <sup>2</sup> )
Wind gust	Angle of attack	$\pm 3$ deg (0.053 rad)
Vehicle elasticity (first mode)	Angle of attack Angle of sideslip	$\pm 30$ percent $\pm 30$ percent
Vent location	Pressure coefficient	Extremely variable — depends on quality of data available
Orifice effective size		
Orifice geometry	Discharge coefficient	$\pm 5$ percent
Flow interference	Discharge coefficient	$\pm 10$ percent
Manufacturing tolerances and structural distortion	Leak size	-----
Compartment volume		
Equipment size and location	Internal flow paths	-----

<sup>a</sup>The perturbations and their effects vary with the vehicle configuration and mission and should be evaluated for each particular case.

If the value of the parameter has been determined for a similar compartment, this value can be used for the initial estimates. Also, if the value of the parameter is appreciably greater than unity, the pressure in a single compartment is usually considered to be nearly the same as the average pressure acting at the vent(s). This, however, applies only if there is a negligible amount of gas from sources in the compartment, if the characteristic time,  $t$ , is as described in Section 4.1.3, and if heat transfer is not occurring at a rapid rate.

In the detailed analyses of the orifice flow, experimental data for discharge coefficients of the type shown in references 4 to 17 should be used, as applicable to the design under consideration. As a minimum, the discharge coefficients used should be applicable in terms of orifice Reynolds number and pressure ratio across the orifice. The local external flow conditions of Mach number and boundary-layer thickness and profile should be accounted for in orifice-flow analysis. Tolerances should be established on the allowable accuracy of the discharge coefficient. The effect of this uncertainty on the compartment conditions should be determined.

In analyzing flow through vents other than orifices, consideration should be given to heat transfer, friction effects, and total pressure losses. Whenever possible, experimental data accounting for these effects should be used. In the absence of such data, analyses should be performed in which extreme variations in pressure losses and heat transfer are considered to determine extreme compartment conditions (e.g., refs. 4 and 19).

### 4.1.3 Compartment-Fluid Flow

The procedure for computation of compartment-fluid flow depends upon the boundary conditions of the compartment. The actual unsteady-flow terms in the equations of fluid motion should be neglected whenever changes in boundary conditions occur slowly (i.e., when the time for an acoustic wave to cross the compartment is far less than the time for a change in the boundary condition). Mathematically, this time relationship can be expressed as follows:

$$\left\{ \frac{t}{L} a \right\} \gg 1 \text{ (nondimensional)}$$

where

$t$  = a characteristic time for the change in boundary condition to occur

$L$  = a characteristic dimension of the compartment

$a$  = the speed of sound of gas in the compartment

When the condition expressed by the preceding mathematical statement holds, the compartment-fluid flow analysis should be performed by describing the changes in compartment conditions in terms of the derivatives of steady-state conditions. When the velocities in the compartment are near zero, the pressure should be assumed to be uniform throughout the compartment. Under these conditions, the problem of flow in the compartment and through the vent system can be formulated as an unsteady, nonlinear, differential-equation system. For such problems, solutions should be obtained by numerical techniques, assuming that steady-state gasdynamic relations can be applied over small time increments, using average properties (ref. 9). These numerical solutions are usually performed with the aid of a high-speed digital computer. (Numerous computer programs exist; refs. 37 and 38 describe two, each of which has special features.)

The mass flow from leakage, engine exhaust, and other sources in the compartment should be averaged over the time step. The net mass change in the compartment should be computed from the mass outflow from the compartment, usually determined from the continuity equation and the equation of state. The mass outflow varies inversely with the square root of the total temperature in the compartment and directly with the instantaneous stagnation pressure. The temperature varies with time because of both outflow and heat transfer within and into the compartment. The temperature variation within the time step should be computed from the energy equation describing the internal gas energy plus the energy transferred to the gas. Finally, when the mass change in the compartment has been calculated from the energy and mass-flow equations, the pressure change in the compartment can be determined by the gas equation of state over the time interval.

If significant temperature stratification is occurring in the compartment (as with compartments adjacent to tanks filled with cryogenic fluids), an analysis involving both time and the appropriate spatial coordinates as independent variables should be performed. Because heat transfer cannot be accurately determined under stratification conditions, no single calculation procedure can be recommended. When such an analysis is performed, it should be supported by test data.

If there are sources of high-momentum flow in the compartment causing nonuniform pressures, special analyses must also be conducted. For example, a source of flow into a compartment must travel a considerable distance before sufficient mixing can occur to dissipate its momentum, and any component, structure, or equipment within at least 10 jet diameters may be subjected to the momentum of the jet, and hence to pressures other than the bulk compartment pressure. First-order estimates of the effects of high-momentum flow may be made by assuming that the flow into or out of the compartment is not affected by the high momentum, and that local disturbances

may be calculated by standard plume-impingement methods. (See Sec. 4 of ref. 1.) If the first-order estimates show that the compartment venting is affected by variations in pressures and temperatures at the compartment vents, a refined analysis should be conducted. In this event, the analysis can be expected to be less accurate.

In unusual cases, the condition for rate of change in compartment boundary conditions,  $\left\{\frac{t}{L}a\right\} \gg 1$ , may not be met, and there is a possibility that traveling pressure waves exist in the compartment. No single practice can be recommended as being adequate for analysis of compartment flow when such waves are present. Acoustic- or shock-wave solutions described in references 4, 27, and 29 may be used with some success. However, these calculations are subject to gross errors and should be verified experimentally.

It should be noted that certain aspects of compartment-fluid flow analysis are empirical, and the variety of assumptions required can result in significant errors. Furthermore, the simultaneous matching of other loads and pressure-differential loads to define any critical combination of these loads is difficult to achieve for two reasons:

1. Maximum values of one load do not occur simultaneously with maximum values of other loads.
2. Maximum burst- or collapse-differential pressures are difficult to define because the differential is composed of the internal pressure which depends on the total trajectory path and the external pressure that depends on the instantaneous trajectory conditions.

For determination of these differentials, it is recommended that an initial analysis be performed which defines burst or collapse pressures by varying the parameters which affect the determination of the compartment pressures (e.g., compartment leakage, external pressure at vents, orifice coefficients, and compartment volume) and the parameters which affect the external surface pressures (table I). The resultant set of extreme surface and compartment pressures should then be utilized to determine an envelope of maximum burst/collapse pressure differentials. Once the critical loading conditions are identified, detailed analyses should be used to eliminate the excessive conservatism resulting from the unrealistic uncoupling between internal and external pressures.

## 4.2 Design Constraints on Vent Selection

When possible, the use of more than two vents exhausting flow outside of the vehicle and located symmetrically around a given circumference of the compartment is

recommended. This will reduce unbalanced pressure loads on the vehicle caused by vented fluid interaction with the external flow field and can help minimize dispersions in compartment conditions due to asymmetries in the external flow field.

It is recommended that vents not be located in regions where the external pressure variation with time cannot be accurately predicted. In general, these regions are near surface discontinuities where shock waves and flow separation may exist, and in regions where shocks from protuberances, fins, and other surface perturbations interact with the boundary layer. Particular care should be taken in determining the location of shock waves because of significant effects of Mach number and Reynolds number on shock location and because of the uncertainties introduced by scale effects in interpretation of experimental data. When the location of the vents is constrained by other considerations to regions of unsteady pressure, analytical predictions should be verified by empirical techniques, or conservative predictions should be used. Care should be taken to avoid placing external vents in regions where flow may be ingested. When internal compartments are interconnected, the placement of internal vents should not cause adverse effects.

The vent system should be selected and located to meet the design requirements after the following basic data are gathered:

- The physical characteristics (volume, wall area, and shape) of the compartment should be defined. All potential sources of flow into or out of the compartment should be accounted for. The external profile of the vehicle in relation to the compartment should be defined to reveal discontinuities and vehicle asymmetries.
- A nominal, nondimensional pressure distribution in the vicinity of the compartment and the variations in this distribution due to trajectory variations, accuracy of pressure data, and external rocket-exhaust interaction should be determined.

The type of vent selected should be the simplest, most reliable device which will meet the design requirements. The various types of acceptable vents and their characteristics are shown in table II.

The ground venting system (e.g., air-conditioning inlets and outlets, or insulation-purging inlets and outlets) should also be considered in the vent selection.

Venting of sandwich panels in reusable vehicles should be carefully considered because of the possibility of a mechanically induced failure due to freezing of ingested moisture.

TABLE II. – TYPES OF VENTS

Type	Advantages	Disadvantages
Orifice	Simple	Fixed area
Tube, pipe, duct	Simple; routed flow path	Fixed area; effects of friction and total pressure losses and effects of heat transfer difficult to predict accurately; accuracy of discharge coefficient questionable
Frangible diaphragm	Simple; operates as an off/on valve which allows orifice size to change (once) when pressure exceeds given level	Uncertain discharge coefficient; may inadvertently open
Ordnance- or mechanically operated panel (e.g., spring-loaded door)	Operates as an on/off valve which allows orifice size to change; opens on command; can be very large	Questionable operational reliability
Valve	Controls mass flow direction; controls pressure level	Questionable operational reliability; accuracy of discharge coefficient questionable

### 4.3 Verification of Vent-System Performance

The decision as to whether or not to test to verify vent performance depends on the applicability of the empirical data used to design a particular vent system, the confidence placed in the analyses, and the relevance of the analyses to the performance of critical components or structures. Tests should be conducted whenever the environment cannot be defined within a required accuracy by analysis, such as in the determination of pressure distribution, vent-flow interaction with external flow, or compartment-fluid flow field.

Wind-tunnel tests should be used to determine the pressure distributions which define the external flow field. Conventional aerodynamic-pressure tests can be used to provide data for the venting analysis if the venting requirements are included in the test definition. The utilization of wind-tunnel data requires careful consideration of scale effects in locating regions of strong pressure gradients.

The interaction between vented gases and external flow field should be verified by duplicating the external flow parameters of local Mach number, local Reynolds number, boundary-layer profile and thickness, and the vent-flow parameters of discharge Reynolds number and pressure ratio. The discharge coefficient may be measured in the same test. The discharge Reynolds number and pressure ratio should be duplicated in tests for determining discharge coefficients in the absence of external flow.

If it is necessary to evaluate the compartment's flow field by experiment, the effects of the external flow field and of the external pressure must be artificially separated because of facility limitations. This can be accomplished by using an equivalent orifice and imposing the appropriate pressure history without simulating velocity on the vent outlet. The simulated compartment should be geometrically correct, but heat fluxes and internal gas sources can be scaled. Not only should momentum-flux and mass-flow levels be scaled, but the rate of momentum-flux buildup and the mass-flow rate changes should also be scaled.

When rapid transients occur, they should be scaled carefully; high-frequency-response instrumentation should be used to collect test data. Because of the difficulty in scaling the time-dependency of these changes while conducting subscale tests, it is recommended that full-scale tests be performed or that checks be made on the effects of variations in scaling parameters in subscale tests.

Subscale tests are often only qualitative, and should be used only after the scale effects are carefully evaluated. Greater confidence can be placed in a subscale test when the gas composition in the test is the actual gas composition, the momentum-flux and mass-flow rates are scaled by the dimensional scale factor squared, and the gas-generator (or rocket-engine) pressures and temperatures are matched to actual conditions. In general, all geometry should be scaled by the dimensional scale factor; however, some dimensions may be altered to improve scaling of boundary-layer thickness and other dimensions.

If explosively or mechanically actuated vent-system components are used, they should be tested with suitable qualification procedures, such as those presented in reference 39.



## REFERENCES

1. Anon.: Aerodynamic and Rocket-Exhaust Heating During Launch and Ascent. NASA Space Vehicle Design Criteria (Structures), NASA SP-8029, 1969.
2. Cassel, L. A.; Davis, J. G.; and Engh, D. P.: Lateral Jet Control Effectiveness Prediction for Axi-Symmetric Missile Configurations. Rept. RD-TR-68-5, Army Missile Command, June 1968. (Available from DDC as AD 836682.)
3. Charwat, A. F.; and Allegre, J.: Interaction of a Supersonic Stream and a Transverse Supersonic Jet. AIAA J. vol. 2, no. 11, Nov. 1964, pp. 1965-1972.
4. Shapiro, A. H.: The Dynamics and Thermodynamics of Compressible Fluid Flow. Vol. I. The Ronald Press Co. (New York), 1953, pp. 91-105.
5. Grace, H. P.; and Lapple, C. E.: Discharge Coefficients of Small Diameter Orifices and Flow Nozzles. ASME Trans., vol. 73, 1951, pp. 639-647.
6. Ambrosius, E. E.; and Spink, L. K.: Coefficients of Discharge of Sharp Edged Concentric Orifices in Commercial 2-Inch, 3-Inch, and 4-Inch Pipes for Low Reynolds Numbers Using Flange Taps. ASME Trans., vol. 69, 1947, pp. 805-812.
7. Peterson, G. S.: Orifice Discharge Coefficients in the Viscous-Flow Range. ASME Trans., vol. 69, 1947, pp. 765-768.
8. Brundin, C. L.: Rarefied Gas Dynamics. Vol. II. Academic Press (New York), 1967, pp. 1235-1256.
9. Muraca, R. J.: A Method for Determining the Time-Dependent Pressures in a Series of Chambers Connected to an External Pressure Whose Variation with Time is Known. Master's Thesis, Univ. of Virginia, 1968. (Available on request from author, care of NASA Langley Research Center.)
10. Vick, A. R.: An Investigation to Determine the Discharge and Thrust Characteristics of Auxiliary - Air Outlets for a Stream Mach Number of 3.25. NASA TN D-1478, 1962.
11. Kalioretenoc, C. A.; Leonar, A. P.; and Frandsen, N. P.: Weight Flow Rates Through Circular Holes in a Flat Plate Immersed in a Subsonic or Supersonic Airstream. NOL-TR-61-125, United States Naval Ordnance Lab., 1963.

12. Romeo, D. J.; and Sterrett, J. R.: Aerodynamic Interaction Effects Ahead of a Sonic Jet Exhausting Perpendicularly from a Flat Plate Into a Mach Number 6 Free Stream. NASA TN D-743, 1961.
13. Walters, W. P.; et al.: Experimental Determination of Generalized Venting Characteristics. NASA CR-61241, 1968.
14. Callaghan, E. E.; and Bowden, D. T.: Investigation of Flow Coefficients of Circular, Square and Elliptical Orifices at High Pressure Ratios. NACA TN 1947, 1949.
15. Dewey, P. E.; and Vick, A. R.: An Investigation of Discharge and Drag Characteristics of Auxiliary - Air Outlet Discharging Into a Transonic Stream. NACA TN 3466, 1955.
16. Anon.: Flow of Fluids Through Valves, Fittings, and Pipe. Tech. Paper 410, Crane Co., 1965.
17. Streeter, V. L.: Handbook of Fluid Dynamics. Ch. 16. McGraw-Hill Book Co., Inc., 1961.
18. Keenan, J. H.; and Kaye, J.: Gas Tables. John Wiley & Sons, Inc., 1954.
19. Struck, H. G.; and Harkins, J. A.: Compartment Venting and Pipe Flow with Heat Addition. NASA TM X-53734, 1968.
20. Bonura, M. S.; et al.: Engineering Criteria for Spacecraft Cabin Atmosphere Selection. NASA CR-891, 1967.
21. Smetana, F. O.: On the Prediction of Gas Flow Rates Through Round Wire Screens. ASME Trans., J. Basic Engineering, vol. 85, series D, no. 4, Dec. 1963, pp. 620-624.
22. Bird, R. B.; Stewart, W. E.; and Lightfoot, E. N.: Transport Phenomena. Chs. 15 and 22. John Wiley & Sons, Inc., 1960.
23. Clark, J. A.: A Review of Pressurization, Stratification, and Interfacial Phenomena. International Advances in Cryogenic Engineering, Proc. 1964 Cryogenic Engineering Conference, Univ. of Pennsylvania, Philadelphia, 1965, pp. 259-283.

24. Eckert, E. R. G.: Heat and Mass Transfer. McGraw-Hill Book Co., Inc., 1959, pp. 449-456.
25. Abramovich, G. N.: The Theory of Turbulent Jets. MIT Press (Cambridge, Mass.), 1963.
26. Zeleznik, F. J.; and Gordon, S.: A General IBM 704 or 7090 Computer Program for Computation of Chemical Equilibrium Compositions, Rocket Performance, and Chapman-Jouguet Detonations. NASA TN D-1454, 1962.
27. Liepmann, H. W.; and Roshko, A.: Elements of Gasdynamics. John Wiley & Sons, Inc., 1957, pp. 107-109.
28. Hayes, W. D.; and Probstein, R. F.: Hypersonic Flow Theory. Academic Press (New York), 1959.
29. Rudinger, G.: The Reflection of Pressure Waves of Finite Amplitude from an Open End of a Duct. J. Fluid Mechanics, vol 3, pt. 1, Oct. 1957-Mar. 1958, pp. 48-66.
30. Pope, A.: Wind Tunnel Testing. John Wiley & Sons, Inc., 1961.
31. Pope, A.; and Goin, K. L.: High Speed Wind Tunnel Testing. John Wiley & Sons, Inc., 1965.
32. Goethert, B. H.: Transonic Wind Tunnel Testing. (Agardograph 49) Pergamon Press (New York), 1961.
33. Anon.: U. S. Standard Atmosphere, 1962, and Supplement, 1966. U. S. Government Printing Office, 1962 and 1966.
34. Anon.: A Reference Atmosphere for Patrick Air Force Base, Florida. NASA TM X-53139, 1964.
35. Anon.: Models of Mars Atmosphere (1967). NASA Space Vehicle Design Criteria (Environment), NASA SP-8010, 1968.
36. Anon.: Models of Venus Atmosphere (1968). NASA Space Vehicle Design Criteria (Environment), NASA SP-8011, 1968.

37. Scialdone, J. J.: Internal Pressure of a Spacecraft or Other System of Compartments, Connected in Various Ways and Including Outgassing Materials in a Time-Varying Pressure Environment. X327-69-524, NASA Goddard Space Flight Center, Aug. 1969.
38. Parker, Coy, E., Sr.: A Computer Program to Calculate the Pressures in the Vented Chambers of the Apollo Spacecraft. NASA-MSC Computer Program F207, NASA Manned Spacecraft Center, Apr. 1967.
39. Anon.: Apollo Applications Test Requirements. NASA NHB 80803, 1967, revised 1970.

# NASA SPACE VEHICLE DESIGN CRITERIA

## MONOGRAPHS ISSUED TO DATE

SP-8001	(Structures)	Buffeting During Atmospheric Ascent, May 1964 – Revised November 1970
SP-8002	(Structures)	Flight-Loads Measurements During Launch and Exit, December 1964
SP-8003	(Structures)	Flutter, Buzz, and Divergence, July 1964
SP-8004	(Structures)	Panel Flutter, July 1964
SP-8005	(Environment)	Solar Electromagnetic Radiation, June 1965
SP-8006	(Structures)	Local Steady Aerodynamic Loads During Launch and Exit, May 1965
SP-8007	(Structures)	Buckling of Thin-Walled Circular Cylinders, September 1965 – Revised August 1968
SP-8008	(Structures)	Prelaunch Ground Wind Loads, November 1965
SP-8009	(Structures)	Propellant Slosh Loads, August 1968
SP-8010	(Environment)	Models of Mars Atmosphere (1967), May 1968
SP-8011	(Environment)	Models of Venus Atmosphere (1968), December 1968
SP-8012	(Structures)	Natural Vibration Modal Analysis, September 1968
SP-8013	(Environment)	Meteoroid Environment Model – 1969 [Near Earth to Lunar Surface], March 1969
SP-8014	(Structures)	Entry Thermal Protection, August 1968
SP-8015	(Guidance and Control)	Guidance and Navigation for Entry Vehicles, November 1968
SP-8016	(Guidance and Control)	Effects of Structural Flexibility on Spacecraft Control Systems, April 1969
SP-8017	(Environment)	Magnetic Fields – Earth and Extraterrestrial, March 1969
SP-8018	(Guidance and Control)	Spacecraft Magnetic Torques, March 1969
SP-8019	(Structures)	Buckling of Thin-Walled Truncated Cones, September 1968
SP-8020	(Environment)	Mars Surface Models (1968), May 1969
SP-8021	(Environment)	Models of Earth's Atmosphere (120 to 1000 km), May 1969

SP-8022	(Structures)	Staging Loads, February 1969
SP-8023	(Environment)	Lunar Surface Models, May 1969
SP-8024	(Guidance and Control)	Spacecraft Gravitational Torques, May 1969
SP-8025	(Chemical Propulsion)	Solid Rocket Motor Metal Cases, April 1970
SP-8026	(Guidance and Control)	Spacecraft Star Trackers, July 1970
SP-8027	(Guidance and Control)	Spacecraft Radiation Torques, October 1969
SP-8028	(Guidance and Control)	Entry Vehicle Control, November 1969
SP-8029	(Structures)	Aerodynamic and Rocket-Exhaust Heating During Launch and Ascent, May 1969
SP-8030	(Structures)	Transient Loads from Thrust Excitation, February 1969
SP-8031	(Structures)	Slosh Suppression, May 1969
SP-8032	(Structures)	Buckling of Thin-Walled Doubly Curved Shells, August 1969
SP-8033	(Guidance and Control)	Spacecraft Earth Horizon Sensors, December 1969
SP-8034	(Guidance and Control)	Spacecraft Mass Expulsion Torques, December 1969
SP-8035	(Structures)	Wind Loads During Ascent, June 1970
SP-8036	(Guidance and Control)	Effects of Structural Flexibility on Launch Vehicle Control Systems, February 1970
SP-8037	(Environment)	Assessment and Control of Spacecraft Magnetic Fields, September 1970
SP-8038	(Environment)	Meteoroid Environment Model — 1970 (Inter- planetary and Planetary), October 1970
SP-8040	(Structures)	Fracture Control of Metallic Pressure Vessels, May 1970
SP-8042	(Structures)	Meteoroid Damage Assessment, May 1970
SP-8043	(Structures)	Design-Development Testing, May 1970
SP-8044	(Structures)	Qualification Testing, May 1970
SP-8045	(Structures)	Acceptance Testing, April 1970
SP-8046	(Structures)	L a n d i n g I m p a c t A t t e n u a t i o n f o r Non-Surface-Planing Landers, April 1970
SP-8047	(Guidance and Control)	Spacecraft Sun Sensors, June 1970
SP-8050	(Structures)	Structural Vibration Prediction, June 1970

SP-8053	(Structures)	Nuclear and Space Radiation Effects on Materials, June 1970
SP-8054	(Structures)	Space Radiation Protection, June 1970
SP-8055	(Structures)	Prevention of Coupled Structure-Propulsion Instability (Pogo), October 1970
SP-8056	(Structures)	Flight Separation Mechanisms, October 1970
SP-8057	(Structures)	Structural Design Criteria Applicable to a Space Shuttle, January 1971
SP-8060	(Structures)	Compartment Venting, November 1970
SP-8061	(Structures)	Interaction with Umbilicals and Launch Stand, August 1970